Innovation Funding Incentive (IFI)

Management of electricity distribution network losses

Executive summary

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1 Introduction

In distribution network management, design policies and standards are established to meet the objectives of achieving network reliability and safety at efficient cost. The consideration of losses has also been important, but has been generally subordinate to network managers' primary objectives of safety and reliability.

Imperial College and Sohn Associates have worked together on an IFI-sponsored project which has examined the opportunities for moving further towards loss-inclusive network design. This is in contrast to the more traditional approach of peak-driven network design, in which the network is primarily developed and designed to meet peak demand in a safe and reliable manner and in which losses have been considered more as a consequence of design and operational management decisions, rather than an explicit design criterion.

In essence, this Study has been undertaken in order to progress with the concept of making distribution networks as energy efficient as is economically possible, raising awareness of the relevant issues and proposing solutions which take more account of losses in network design.

Copper and iron losses are an inherent feature of electricity distribution. They cannot be eliminated but this Study explores how the network can be managed such that losses are economically efficient. The conclusions on better management of network losses[1] are based upon evidence, views and opinions concerning not only what is technically feasible and practical, but also what is economically justified.

The specific objectives of this work are three-fold:

1. **Understanding losses:** The Study provides both background and insight on distribution network losses as a precursor to control of losses in future network management;
2. **Loss inclusive network design:** Traditionally, network design has been driven by requirements of delivering power reliably and safely. This has not explicitly included the cost of losses and the economic impact of carbon dioxide emissions. A key objective of this work is to now consider losses as inclusive within the network designs of the future, including the requisite obligations and standards to ensure delivery;
3. **Future developments:** The Study has researched other work which in the future may contribute to further improvements in loss management, extending the consideration of losses to the heat generated from electrical loss. The objective of this work has been to review the extent of knowledge and experience of such work and to assess its potential value.

It is anticipated that this work will provide insight into losses which fits with the developments in whole systems energy modelling designed to help policy-makers meet the challenges of decarbonisation, energy security and cost-effectiveness across the whole energy chain.

[1] The term "network losses" is used throughout this Report interchangeably with "technical losses".

2 Key points

Many issues relating to electricity distribution loss management have been examined and the Recommendations which are presented throughout the Report are listed in Annex 1.

In networks infrastructural businesses, it takes a long time to make significant changes to the overall assets and network managers will only be able to make a real impact on total network losses incrementally. Plans are being developed by DNOs to address losses and to satisfy Ofgem's requirements for effective loss management in the RIIO-ED1 Price Control period (2015-2023). This will include developing the capabilities to return to incentive-based loss regulation in the following Price Control Period, RIIO-ED2, from 2023 onwards.

From our work we make five key observations for future policy:

1. **Investment for network energy efficiency.** For future electricity consumers, there are compelling reasons to develop networks and demand-side relationships to ensure that the distribution system is energy efficient. Energy efficiency may be defined by comparing the economic value of avoided loss against the incremental cost of such loss avoidance. The economic value of avoidable loss includes both the forward cost of energy and the value of carbon abatement. It is possible to develop a strategy which resolves the dilemma of over- or under-investing today in relation to the requirements of future customers;
2. **Regulation.** There are strong obligations on DNOs to operate the networks in a safe manner and to a prescribed level of reliability (Engineering Recommendation P2/6). However there is no similar requirement to design the network to a prescribed level of losses, as is the case in some other countries. Loss-inclusive network design is now economically justifiable and can be developed within the next price-control period, RIIO-ED1, in order to provide a return to incentive-based regulation of loss management in RIIO-ED2;
3. **Understanding losses.** With modern computing power, good data management and additional network monitoring, the location and magnitude of losses in specific parts of the network can be much better understood in order to assist in selecting the right investment options. Similarly, the confidence in reported overall levels of network loss can be improved in order to assist network owners, managers, government and regulators in shaping their views of the energy efficiency of the distribution network;
4. **Loss-inclusive network design techniques.** There are several identifiable opportunities for cost-effective management of losses through interventions on the existing network and design of future networks. Smartgrid enabling technologies, including smart meters, will be invaluable in making these improvements although there is a tension between some objectives of smartgrid solutions and the pursuit of network energy efficiency;
5. **Valuing heat**. The remit of the DNO may extend beyond the management of electrical loss to the management of the consequences of electrical loss, namely heat, which has potential value in those locations where it may be harvested and used. There are several examples of heat-valuation but better-controlled field trials are required in order to progress towards commercial applications.

3 Features of network losses

This Study has examined a variety of factors which drive the estimated levels of loss in electricity distribution networks.

3.1 Network modelling and analysis

Much of the work has been conducted using network modelling and analysis tools, to both understand the drivers of losses and to evaluate the potential for better loss management through loss-inclusive network design.

It is demonstrated that these methodologies for loss studies on representative networks using assumed network parameters and load profiles, provide a reasonable indicative view of losses on different types of GB network – urban, semi-urban, semi-rural and rural, as shown in Figure 1.

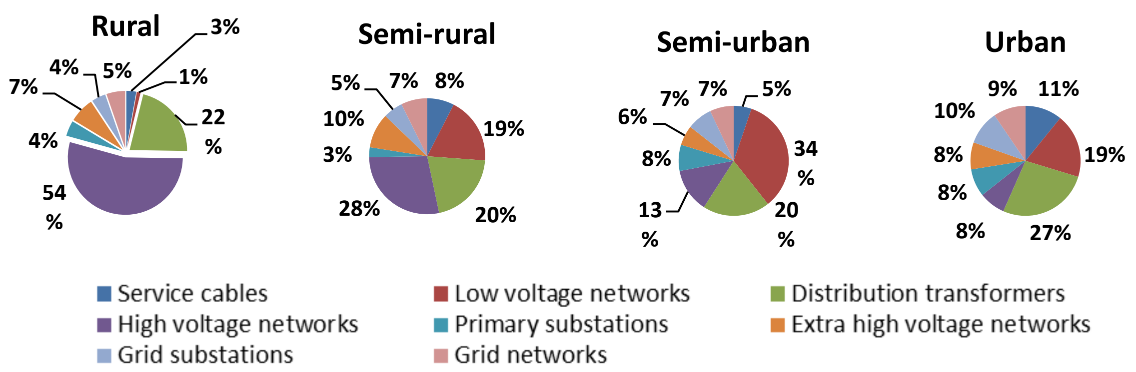

Figure 1. Breakdown of losses across distribution networks in four types of network

The analysis of the breakdown of losses across a typical GB distribution network correlates well with Distribution Network Operators' (DNOs') own network studies, with the majority of total loss occurring in the HV networks (particularly in rural networks), HV/LV distribution transformers and the LV networks (particularly in semi-urban network), but with a wide variation of the distribution of losses across the different network types.

We consider that there is considerably more knowledge of losses to be discovered using these techniques and it will be of benefit to DNOs to become increasingly familiar with such capabilities for loss modelling and analysis.

Recommendation 1: The network modelling and analysis tools used in the study are based on calibrated representative network models data. Given the increasing importance of losses, it would be appropriate that DNOs establish the capability of modelling and evaluating loss performance of their present and future networks, under different future development scenarios.

3.2 Power factor and losses

Departure of load power factor from unity will increase losses in distribution networks. Table 1 presents the Increase in losses in LV and HV networks due to various power factors of loads and in different representative network types. We observe that greatest increase of losses is in rural type networks when compared to urban networks. For example, if the load power factor is 0.95 the losses are between 5-10% greater when compared with the unity power factor case.

Table 1. Impact of loading power factors on losses increase for different representative network types

Power factor	Representative network types			
	Urban	S-urban	S-rural	Rural
1	0	0	0	0
0.95	5.3%	6.9%	7.7%	10.1%
0.9	10.5%	13.2%	14.6%	18.9%
0.85	16.3%	20.1%	22.1%	29.7%
0.8	22.7%	27.9%	30.6%	-

We also observe that poor power factors, e.g. less than 0.9, would significantly increase losses.

The range of benefits of improving power factor to unity for various network types is given in Table 2.

Table 2. Benefits (£/KVAr) of improving power factor to unity for different network types

Power factor	Urban	S-urban	S-rural	Rural
0.95 → 1	15 - 31	28 - 59	41 – 88	50 - 106
0.9 → 1	46 - 99	84 - 179	122 – 259	146 - 310
0.85 → 1	42 - 89	74 - 158	106 – 225	140 - 298
0.8 → 1	93 - 197	164 - 349	236 – 502	-

The lower values of benefit in the range correspond to 9% discount rate over 20 years and the higher values correspond to 3.5% discount rate over 45 years.

Power factor improvements in different network types range in value from £15 per KVAr (0.95→1, Urban) to £502 per KVAr (0.8→1, Semi-rural). As the cost of reactive compensation is less than £50/kVAr, it is clear that in case of the power factor being less than 0.95, it may be economically efficient to improve it.

One of the key challenges associated with establishing the business case for power factor correction is the lack of data associated with active and reactive power demand in LV and HV networks. Increased level of measurements and general visibility of distribution networks, supported by various smart grid initiatives, could be potentially be used to carry out systematic data collection associated with the power factor. This could then be supported by more comprehensive analysis of the impact of power factors on network losses and appropriate evaluations of the economic case for improvements in power factor.

Furthermore, it may be appropriate to review the incentives in relation to power factor. There has been longstanding tradition in the electricity industry to encourage and incentivise end-consumers to improve power factor although the impact of power factor penalties within DUoS charges and supply contracts are not necessarily cost-reflective.

Recommendation 2: DNOs to carry out more systematic data gathering associated with power factor to assess the materiality of the issue and to enhance the understanding of the costs and benefits of power factor correction at consumers' premises. The business case for power factor correction may then be developed.

3.3 Phase imbalance

The effect of imbalance on network losses is non-linear and, from our calculations, there is a significant increase in losses over approximately 20% imbalance.

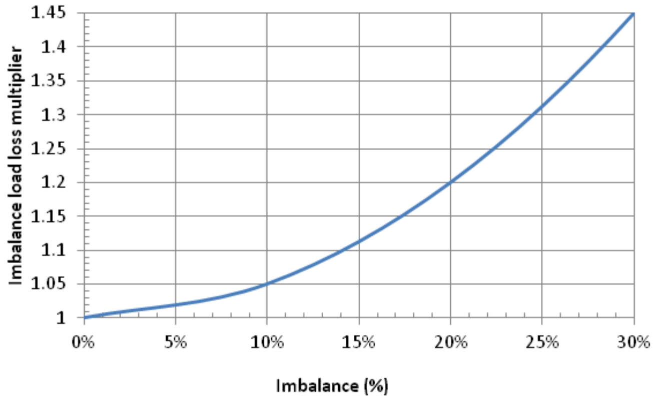

Figure 2. Effect of phase imbalance on losses

Even in the case that end consumers' loads are equally allocated among phases, actual loading of different phases in different times will be different which will lead to increase in electricity losses driven by imbalance.

The benefit of reducing imbalance is proportional to the feeder length. For example, for an underground feeder of the total length of 1.1 km and the level of imbalance of 30%, the possible benefit or reducing losses is in the range from £2,500 to £5,300. It is likely that the many other advantages of balancing phase e.g. enhanced network headroom, both thermal and voltage and reduced radio interference, will add to the benefits side of any business case. Furthermore, it is not clear if application of two-phase 11kV overhead lines is economically efficient, particularly when increase in network losses are considered.

This indicates that the benefits of phase balancing may be significant in some cases. Although there are several individual cases where phase imbalance is potentially very significant, the overall materiality of the problem is not well understood. Furthermore, the options for phase balancing in the existing networks and their costs are not well established. This may require a demonstration project that could build on much of the current innovation focused on measurement and monitoring of the network, and test emerging power electronics based technologies that may deliver tangible reduction in imbalance, in addition to providing power and/or voltage control.

In addition, it is desirable to consider developing a set of comprehensive policies and procedures relating to the avoidance of further increases in imbalance, particularly when connecting new customers.

Recommendation 3: Further work is required to assess the extent of the imbalance problem and to test various solutions, which will not only reduce losses but deliver many other benefits of a well-balanced network. It may be appropriate to develop policies and working practices for avoiding excessive imbalance in future.

3.4 Cable tapering and impact of non-diversified loading in loss calculations

In GB, there has been a longstanding tradition of designing LV networks with reducing conductor sizes at greater distances along the feeder from the distribution substation. Compared with a non-tapered approach, this has enabled lower costs of construction, but has reduced network operational flexibility and has generated higher losses than would be the case with the same cable sizing along the feeder.

The impact of tapering on losses has been assessed on a tapered network, with cable reducing in size from 300mm^2 to 185mm^2 and 95mm^2. This is compared with a non-tapered system with 300mm^2 cable. The impact of tapering on losses, with three assumptions of load distribution, is shown in Table 3.

Table 3. Losses increase due to conductor tapering

Load distribution	Losses increase due to tapering
Linearly decreasing	36%
Uniformly distributed	57%
Linearly increasing	69%

A hypothetical set of tapered and un-tapered networks has been analysed to estimate the overall least-cost solution which takes losses into account. It is demonstrated that, whilst the tapered network may be of least cost, the cost differences are marginal and the case for un-tapered network may be very strong especially when other valuable features such as flexibility, standardisation, "future-proofness" and LV network reconfiguration are considered.

It is unlikely that losses only will drive the policy on tapering. There are more significant issues such as volt drop and future network flexibility which affect the decision-making. However, we note that some DNOs do not apply tapering in their LV design for interconnected LV networks. A loss-inclusive approach to network design creates further bias of policy towards not tapering. The uncertainty of demand of electric vehicles and future retrofit of micro-generation would further justify not tapering, as being a prudent and relatively low-cost means of developing the flexibility required within the LV network to support the low-carbon economy. In order to reach a universal view in GB of not tapering, further analysis may be required of the instances in which tapering has been a limiting factor on the options available to the network designer when accommodating new load or microgeneration.

The case for not tapering LV feeders is further reinforced by the analysis of the impact of non-diversified load profiles that are particularly relevant for feeder sections supplying small number of consumers. To capture the impact on losses from load variations, five-second time power flow assessments are carried out.

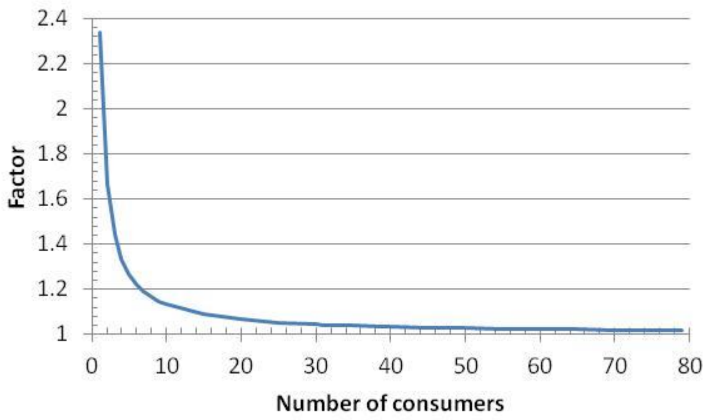

Figure 3. Modelled loss factor for diversified load profiles

The results indicate that calculated losses from a non-diversified load profile are 2.34 times higher than those less accurately calculated from diversified loadings. Using similar high-speed time-slicing, the losses in the LV mains network i.e. after diversification, are 10% higher than would have been calculated using half-hourly data. This clearly demonstrates that demand volatility at the edges of LV network including services cables, is the key driver for relatively higher losses in these parts of the network when compared with sections supplying larger number of consumers, which further reinforces the case of not-tapering of LV distribution networks.

Recommendation 4: In order to reduce losses and provide future flexibility within LV networks, LV tapering policy may be re-examined.

Recommendation 5: The inaccuracy of loss calculation using half-hourly data at the edges of the LV network should be recognised when conducting network studies.

3.5 Voltage control driven load reduction

The Study has included analysis of the effect of reducing voltage in terms of reducing demand and reducing network losses, as presented in Table 4. Under different energy cost assumptions and different levels of voltage reduction a value is determined as the justifiable cost of installing voltage control on distribution transformers. This work gives a useful demonstration of the scale of loss reduction which may be realised and how that may differ between different types of network.

Table 4. Reduction in losses with energy supplied

Energy reduction (%)	Loss reduction for semi-urban network (%)	Loss reduction for semi-rural network (%)
2.5	5	9
5	9	13
7.5	14	17
10	18	21

There are many practical issues to consider such as the impact of voltage regulation and the ability or otherwise to maintain customers' supply voltage within statutory limits. Also, the assumptions which have to be made regarding customer response to lower voltage over time affect the accuracy of this analysis.

This work focussed on including losses in LV design proposals and may assist in justifying voltage control at distribution transformers or application of advanced in-line voltage regulators and consumer-end voltage control based energy efficiency technologies. Additional voltage control is being considered by DNOs in order to manage the uncertainty of new load and new microgeneration on LV networks.

Recommendation 6: Benefits of active voltage control in LV distribution network may be very beneficial and comprehensive assessment of the opportunities to further reduce network losses should be investigated.

3.6 Impact of active network management on losses

Introduction of various smartgrid technologies and corresponding active network management techniques is aimed at reducing network costs and timescales of connecting new low carbon generation and demand technologies. Enhancing the ability of existing distribution networks to integrated new generation and demand through smart grid concepts will lead to increased utilization of the network and consequently increase in losses.

A previous study considered alternative active network management techniques to facilitate connection of a wind farm to the existing 33 kV network shown in Figure 4. Voltage rise in this case is the key barrier that limits the amount of generation that can be connected to the existing network.

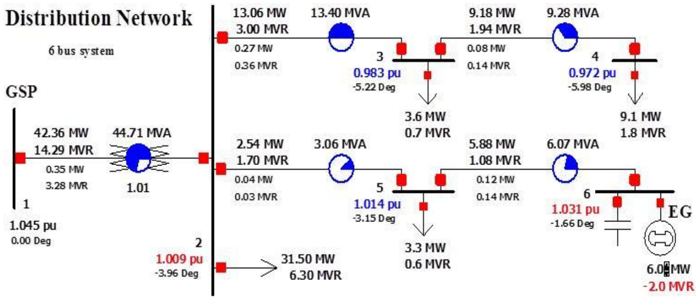

Figure 4. 33kV network model showing maximum loading conditions

The benefits of four active network management techniques in term of enhancing the ability of the network to accommodate increased penetration of wind generation are modelled: generation curtailment, power factor (PF) compensation, area-based OLTC voltage control, and in-line voltage regulators.

For each set of measures the wind generation capacity is increased from 4MW to 20MW in 2MW steps and the annual energy produced is calculated. The base case is provided by applying the standard limit to the increase in voltage at the connection point which would only allow 6MW of wind capacity to be connected. In Figure 5 the lighter bars represent the net energy generated in the course of one year, while the darker bars represent the curtailed energy.

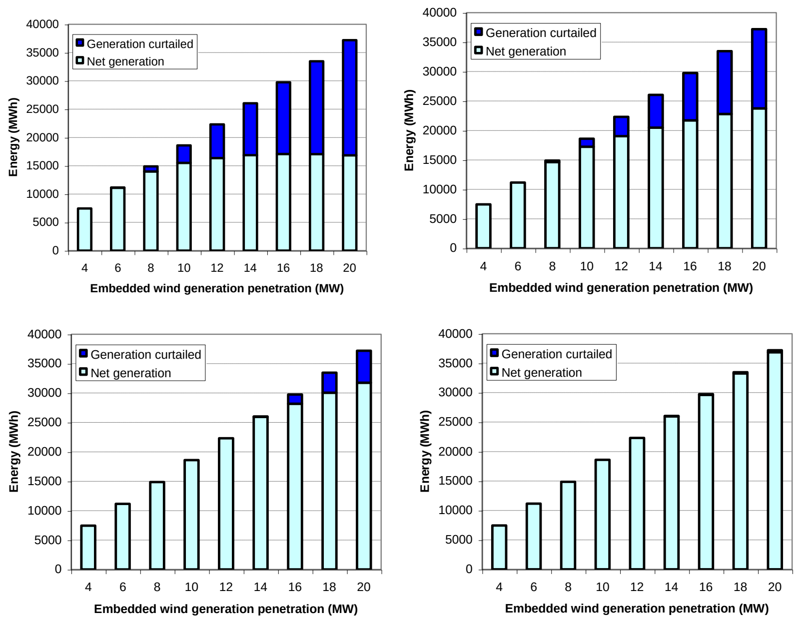

Figure 5. Benefits of four alternative ANM schemes: 0.98 PF, 0.95 PF, Area based OLTC, Area based OLTC with in line voltage regulation

We observe that the least effective is the scheme with generation curtailment and power factor compensation (around of 8MW of generation would be connected), while the most effective one would involve area based voltage control and the application of in-line voltage regulation (around 20MW of wind generation can be connected to the network).

Given the interest in this study, analysis of losses is carried out to illustrate how different active network management techniques used to connect a wind generator may affect losses as shown in Figure 6.

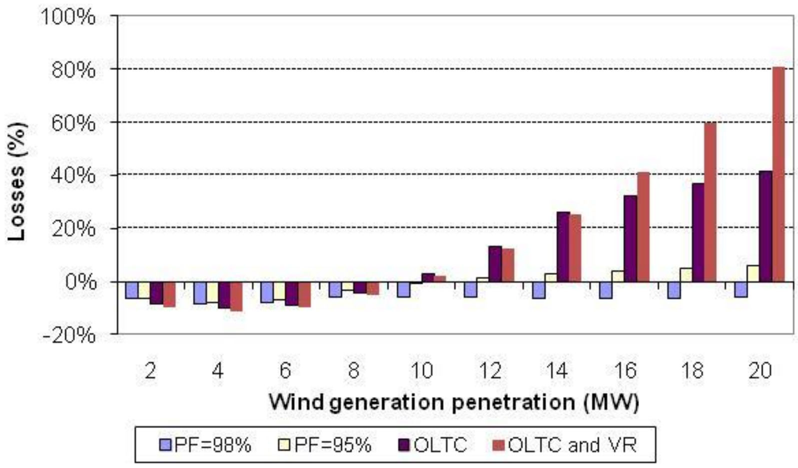

Figure 6. Impact of ANM schemes on network losses for various level of penetration of wind generation

We observe that the application of advanced active management techniques that would maximise the utilisation of existing networks may increase losses in the local network very significantly.

In terms of overall economics, the increase in losses may be efficient when "traded" against the facilitation of low-carbon generation connections and avoided network reinforcements. Nonetheless network loss increases may be also described as a decrease in energy efficiency and as such, undesirable.

There is clearly a significant interaction between the view of future networks in which active network management solutions may be deployed to improve utilisation and avoid network reinforcement and enhancement but which has the associated effect of increasing losses.

Another study is carried out to demonstrate the impact of smart charging, employed to enhance the ability of existing networks to accommodate electric vehicles (EVs). As smart charging increases the utilisation of the network, losses will increase as shown in Figure 7.

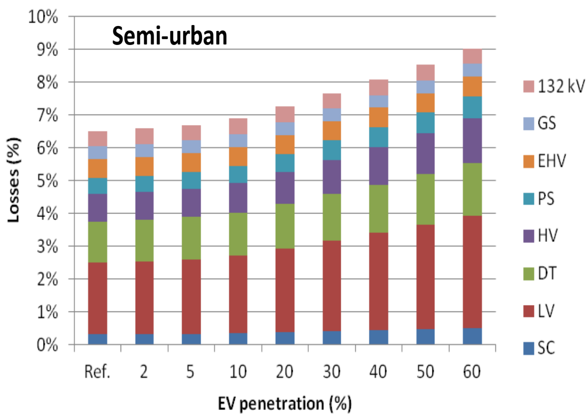

Figure 7. Impact of EV penetration on losses in semi-urban network; smart EV charging

We observe that with penetration of electric vehicles about 50%, with smart charging needed to integrated electric vehicles within the existing network, the increase in losses will be more than 30%.

There is clearly a significant interaction between active network management techniques deployed to improve utilisation and avoid network reinforcement and the associated effect of increasing losses. The current programme of smartgrid technology developments provides both “loss-favourable” technologies such as profile-flattening techniques[2] but also “loss-adverse” solutions such as dynamic line ratings and solutions which allow the inbuilt capacity for network resilience to be used for normal operating conditions with load-shedding in circumstances of network failure.

The critical policy matter in the context of this Study is that the options for investment should consider the long-term impact on network losses.

Recommendation 7: When considering active network management solutions and technologies to facilitate low-carbon connections, the impact on losses should be given full consideration.

4 Loss inclusive network design

The principle behind this work is that the GB distribution networks should be designed with consideration of the economic value of losses and that there should now be a departure from the traditional approach of designing networks for safety and reliability at the lowest capital cost. It is proposed that the lowest cost in future should include the valuation of losses, which should be an input to the design requirement, not a consequence of how the network has been designed.

With an understanding of losses, the Study has then considered the economic justification for techniques which may be included as “loss inclusive network design”.

4.1 Modelling assumptions

In order to assess cost benefits, evaluation methods have been applied with the following inputs:

- Minimum and maximum energy costs at peak demand and low demand with an conservative average cost just below £50/MWh, with carbon prices not included,
- Costs of network equipment,
- Various capitalisation parameters, including the RIIO-ED1 guidelines of 3.5% discount rate over a period of up to 45 years.

4.2 Asset utilisation

One of the most significant outcomes from the Study is the overall least-cost level of asset utilisation which would be justified if no other factors, such as practicality and affordability, were to be considered.

(a) Loss inclusive design of cables and overhead lines

The results in Table 5 show the outcome of the analysis of economic maximum network loading as a percentage of full loading. E.g. if losses were the only consideration, an LV cable being sized according to the RIIO-ED1 capitalisation guidelines of 3.5% discount rate up to 45 years, would be operated at maximum demand no higher than 12-25% of its thermal rating. An HV overhead line would be matched to a maximum demand no higher than 8 -14% of its thermal rating.

[2] Typically, this includes some of the Demand Side Response innovations and some of the current developments in electricity storage

Table 5. Least-cost maximum loading (%) for various electricity costs, discount rates and expected life of assets

Assets		High electricity cost			Low electricity cost		
		Discount rate					
		3.5%, 45 years	4%, 20 years	9%, 20 years	3.5%, 45 years	4%, 20 years	9%, 20 years
Cables	LV	12 - 25	16 – 32	20 – 39	18 - 35	23 – 45	28 – 55
	HV	14 - 27	18 – 35	21 – 43	19 - 39	25 – 50	30 – 60
	EHV	17 - 33	22 – 43	27 – 52	24 - 47	31 – 61	37 – 74
OH lines	LV	11 - 19	14 – 24	18 – 30	15 - 27	20 – 35	25 – 43
	HV	8 - 14	11 – 18	13 – 22	12 - 20	15 – 26	18 – 32
	EHV	10 - 18	13 – 22	16 – 28	14 - 25	18 – 32	22 – 39

The figures shown are the range of percentage maximum loading under different investment criteria and different assumptions of electricity cost. Note that the Ofgem guideline for forward pricing of sustainable electricity saved is £48.42/MWh with an additional avoided loss value based on carbon abatement. We note the figures of maximum network loading in Table 5 are conservative, and could be even lower, as the analysis did not included carbon prices and was based on relatively low energy prices of £45/MWh, particularly in the light of the recent announcement that the strike price for new nuclear would be £92.50/MWh.

In summary, the results indicate that under various scenarios, low levels of network loading can be justified in order to economically optimise the network design. This is essentially re-defining the economic rating of plant and equipment based upon the chosen parameters for valuation of losses. From examination of DNO's Engineering Specifications (quoted in Engineering Recommendation G81 Appendices for each DNO), we identify that DNOs are specifying larger conductors than is required to carry peak load, and we also note the differences in approach being taken between DNOs.

There will be many practical reasons for limiting the physical size of conductors e.g. strength limitations of supports for overhead lines, or complications in connection of large cables to smaller cables, but the use of conductors which are larger than the least-cost solution is economically justified when including losses in the design considerations.

In view of the inconsistencies in sizes and Ofgem's latest views of loss management, it may be beneficial to review design standards to specify economic ratings based upon DNOs' guidelines of valuation of future avoided loss which may or may not align with Ofgem's guidelines.

(b) Loss inclusive design of distribution transformers

Table 6 shows the outcome of the analysis of economic network loading of distribution transformers. It is interesting to observe that transformer capital costs are similar to the cost of losses (discount rate of 3.5% over 45 years) and that the optimal utilisation of transformers may be between 60% and 100%. Note that the minimum overall costs, in cases of peak demand being 500kVA and 630kVA would be achieved by installing an 800kVA transformer.

Table 6. Least-cost Distribution Transformer (discount rate 3.5% over 45 years)

Rating (kVA)	CAPEX (£)	Peak demand (kVA)	Annual cost of load losses (£/year)	Annual cost of no load losses (£/year)	Cost of losses (£)	Total cost (£)	Utilisation
315	13,137	316	411	310	16,238	29,375	100%
500	14,168		233	457	15,526	29,694	63%
630	15,020		175	546	16,200	31,220	50%
500	14,168	500	586	457	23,450	37,618	100%
630	15,020		438	546	22,130	37,150	79%
800	15,199		283	565	19,084	34,283	63%
500	14,168	632	936	457	31,342	45,510	126%
630	15,020		701	546	28,036	43,056	100%
800	15,199		453	565	22,902	38,101	79%

This clearly demonstrates the significant impact that losses may also have in choosing ratings of transformers. We stress that in case of application of low-loss transformers, the optimal utilisation of transformers will be 100%.

Recommendation 8: There is a clear case for fundamentally reviewing cable and overhead line ratings to ensure that future loss costing has been included in the economic rating calculation. This could be based on Ofgem's loss investment guidelines or on loss-inclusive network design standards.

4.3 Low-loss transformers

Table 7 shows the losses in the present design and low-loss transformers, including dry and liquid-immersed low-loss technologies. We observe that low-loss transformers improve significantly both load loss and no-load loss performance. We also note that the losses in significant proportion of existing distribution transformers are higher than losses in the present designs.

Table 7. Losses in standard and low-loss transformers

Rating (kVA)	Present Transformers		Low loss (dry type)		Low loss (liquid-immersed)	
	Load loss (W)	No load loss (W)	Load loss (W)	No load loss (W)	Load loss (W)	No load loss (W)
315	4800	700	3877	496	2800	288
500	6860	1030	5630	722	3900	408
630	8150	1230	7100	880	4600	480

The analysis in this study was based on a cost-benefit analysis of choosing low-loss distribution transformers compared with lower-cost higher loss transformers.

Table 8 presents the additional investment cost in low-loss transformers over and above the conventional high-loss designs. Given the savings in losses, such expenditure would be efficient.

Table 8. Breakeven additional cost of low-loss transformers over classical type

Rating (kVA)	Breakeven additional cost of low loss transformers (£)	
	Dry type	Liquid-immersed
315	2,452 – 3,651	5,117 – 7,618
500	3,492 – 5,199	7,637 – 11,369
630	3,547 – 5,281	9,217 – 13,721

The results indicate that in many cases it will be economic to purchase the more expensive low-loss transformers (ranges of costs correspond to ranges in discounts rates)

This is an area of policy in which one would expect best practice to prevail throughout GB. In this context it would desirable to develop GB wide clear policy in terms of discount rates, investment periods and energy and carbon-abatement costs that are consistent with the GB energy and carbon policy, and this is an important area for dialog between industry, regulator and government.

Recommendation 9: The transformer loss calculations indicate that the benefits of investing in low-loss transformers may be significant and this should be considered further to establish or otherwise the low-loss transformer business case in line with UK energy and carbon policy.

4.4 Early replacement of assets

Analysis was carried out to assess the business of case of loss-driven early replacement of assets i.e. if consideration of losses may justify asset replacement ahead of need, in advance of them becoming overloaded or unreliable. We note that the phrase "ahead of need" has been often-used in networks policy discussions but this has invariably been in the context of the need for capacity, safety, reliability and in some cases environmental issues e.g. pollution, but has never considered losses to be at a target level.

This work shows that early replacement of transformers may potentially be justified and we note that some DNOs have included such a programme in their Business Plans. Table 9 shows the ranges of breakeven transformer replacement costs at which it would be efficient to replace 20-years old high-loss transformers with low-loss designs. (The ranges shown correspond to different discount rates.)

Table 9. Break-even cost for early transformer replacement

Rating (kVA)	Breakeven transformer replacement cost (£)	
	Dry type	Liquid-immersed
315	4,538 – 6,756	7,203 – 10,723
500	6,504 – 9,683	10,649 – 15,854
630	7,149 – 10,643	12,818 – 19,083

Note that these breakeven replacement cost are conservative and could be significantly higher, as the analysis did not include carbon prices and was based relatively low energy prices of £45/MWh, particularly in the light of the recent announcements that strike price for new nuclear would be £92.50/MWh.

On the other hand, our analysis shows that early replacement of cables is not economic, bearing in mind the cost of excavation and re-instatement in addition to the cable purchase and laying costs.

The analysis in the Report, based on our assumed costs and loss performance of old and new transformers, supports such decisions. We understand from one DNO that the scale of early replacement being conducted is not constrained by a lack of economic justification for this work, but the practical resource limits of how much replacement work can be physically achieved in the period of the Business Plan.

Recommendation 10: In future, losses may drive early asset replacement when economically efficient. If early replacement programmes are economically justified and capable of being funded, appropriate resources would need to be made available to facilitate delivery of such programmes.

4.5 Transformer density

Our earlier analysis indicated that increasing the density of secondary distribution substations in cases when feasible, may enhance the ability of LV distribution networks to cost effectively integrate low carbon generation and demand technologies. In the Report we describe the scenario of strategically increasing the density of HV/LV transformers on the network to reduce the length of LV feeders and hence the network losses. We conclude that this may lead to a 10-20% reduction in overall network losses. There may be practical factors that may prevent this:

- the LV cable configuration does not allow sufficient LV feeders to be looped into or diverted into a new distribution substation;
- additional substation sites are unavailable; and
- the HV network is not suitably configured to accept additional substations.

However, the option to introduce additional secondary substations may be compared with other means of reinforcement such as laying new LV cables or replacing existing LV cables with larger ones. Our analysis indicates that there may be instances where this may be cost-justified.

In those cases where LV network design changes are required – usually to accommodate new buildings or for reinforcement, then the LV design work can take losses into account when making the choice whether to reinforce the LV network or include additional substations.

Recommendation 11: Network designers may consider the option of installing additional distribution transformers to minimise LV network reinforcement cost and reduce losses.

4.6 Rationalising HV and EHV voltage levels

The transition to a low-carbon economy may require fundamental changes in network design in order to facilitate cost-effective integration of low-carbon technologies such as heat pumps, electric vehicle charging points and distributed generation[3]. In particular increasing connections of heat pumps, distributed generation and electric vehicles is anticipated and it is appropriate to consider if the present network design and voltage levels are optimal for the future.

The Study has included an assessment of the impact on losses of selecting alternative voltage levels for various network types. A typical outcome in urban networks, as shown in Figure 8, indicates a sizeable reduction in losses which can be achieved on EHV and HV networks.

[3] Some DNOs have experienced a very significant increase in connection of distributed generation which is already re-characterising some parts of their networks.

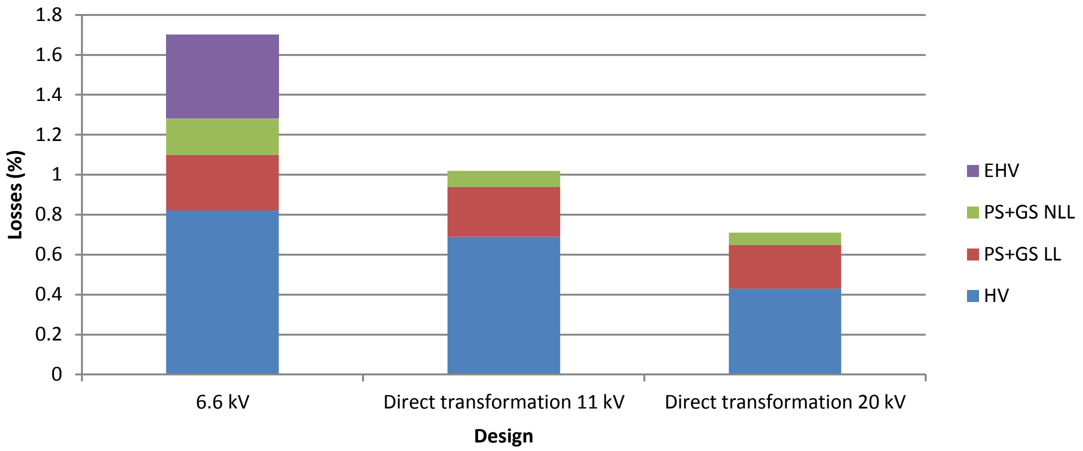

Figure 8. Losses in distribution systems with various voltage levels; HV – high voltage, PS – primary substation, GS – grid substation, LL – load losses, NLL – no-load losses, EHV – extra high voltage (33 kV)

Clearly, a major strategic long-term decision is required to design networks to alternative voltage levels. This will not be taken lightly, nor will it be made based solely on losses. However, the Study illustrates that by applying the principle of loss-inclusive design, the business case will be different when making decisions such as installing 20kV network or specifying more EHV/HV direct transformation.

The analysis provides a useful input to long-term thinking of network voltages and provides an example of how losses valuations may be incorporated into the optimal choice of voltage for future networks.

We have carried out further studies of voltage rationalisation on GB typical networks. An illustrative example of semi-urban network is presented in Figure 9 that shows breakdown of losses (left) and the overall network cost (right) in four and three voltage level network designs. The overall losses are about 30% lower and total cost about 20% lower in direct transformation designs.

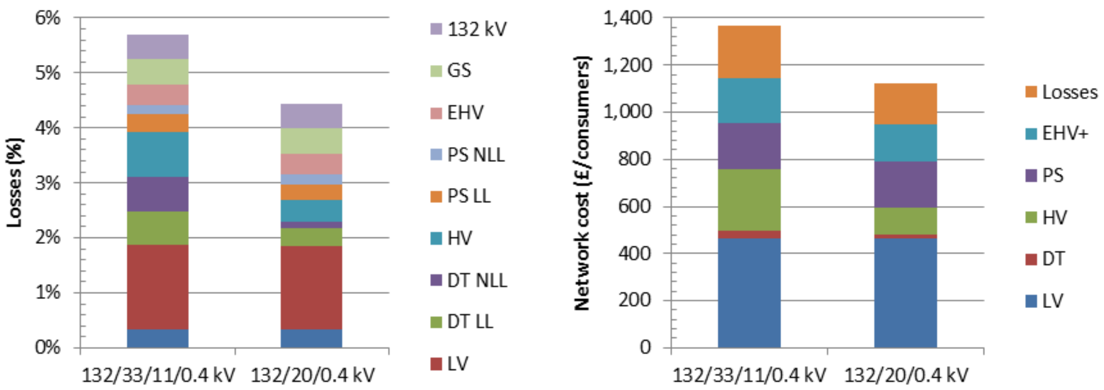

Figure 9. Losses in distribution systems with various voltage levels; LV – low voltage, DT – distribution transformer, HV – high voltage, PS – primary substation, EHV – extra high voltage (33 kV), GS – grid substation, 132 kV – grid network, LL – load losses, NLL – no-load losses

Recommendation 12: In the light of future developments, particularly in relation to the integration of low carbon demand and generation technologies, it may be appropriate to reconsider long-term distribution network design. This may take a strategic view of future voltage levels and include consideration of losses in the decision-making.

4.7 New materials, plant and equipment for loss-inclusive network design

From both the technical analyses of network losses and the economic analyses of cost/benefits of loss mitigation, we conclude that much can be done to move towards energy efficient distribution networks, in which network loss is managed at its economic level. We also conclude that this can be achieved using conventional plant and equipment, in addition to the new smart grid and ANM solutions emerging from recent developments within various network innovation funding arrangements.

However, it is concluded that new forms of transformer designs and new conductor materials for more cost-effective solutions are not readily apparent and are unlikely to feature in network design for many years to come. Perhaps the most relevant development is an interesting trial of superconducting cable in Essen, Germany. In this project, which was justified on grounds of avoiding substations in a very congested part of the city, a 1km high-voltage cable connecting two transformer substations in the Essen area is being replaced with a superconducting three-phase, concentric 10 kV cable with capacity of 40 MW.

4.8 Support requirements for loss-inclusive analysis and design

During our studies we held various discussions with systems providers, other consultants and DNO personnel on the suitability of network modelling and analysis tools. We considered IPSA, DINIS, Powerfactory and WinDebut and came to some general conclusions:

- Modern power network modelling and analysis tools are functionally rich and can readily analyse losses. The limitations on how engineers may be supported in loss analysis have not been the computing technology and algorithms but the lack of data entry into the systems and possibly the lack of priority being ascribed to loss management under current policy. For example, we identified a situation where Windebut was being used extensively for LV network design in which the loss valuation was set at the default value and had not been reviewed to take account of the DNO's latest policy on valuation;
- To adapt the technologies to improve the presentation of losses including highlighting "hotspots" is relatively simple. In most systems we understand that changes may be made to identify and highlight losses on user-friendly displays for less than £0.5m;
- Systems can be developed and data can be acquired, validated and managed according to whatever requirements are set for effective loss management;
- The further development of the tools to provide more accurate loss calculations will be required in order to achieve loss-inclusive network design. In particular there will be requirement for analysis under multiple time-slicing;
- Present tools do not readily support optimisation of the alternative active network management techniques particularly those that involve time-coupled network optimisation such as smart charging of EV, or demand side response, and therefore assessing the impact of smartgrid technologies on annual losses may be very time consuming;
- The existing commercial tools can support network design, but do not automatically carry out cost-benefit analysis through balancing cost of investment and annual operating costs, across multi-year time horizons;
- There is a number of alternative modelling tools designed for strategic network planning that consider losses, such as Imperial's Load Related Expenditure model which was used to inform ED1 business planning or the Strategic System Investment Model that considers investment in primary and smart technologies across multi-year planning time horizons.

For loss-inclusive network design to be embraced by GB DNOs such that all investments take account of the latest approach to capitalising the value of loss avoidance, then network design tools should be refined to support design engineers. The changes to systems and processes should not only deal with the technical requirements but should also be seen as part of a process of inculcating change in priorities such that energy efficiency may become more significant in the overall design than has been the case in the past.

Recommendation 13: A review of DNOs' network modelling and analysis tools and capabilities may be required to support design engineers in applying new policies and processes relating to loss-inclusive network design.

5 Valuing heat generated by network loss

Utilisation of waste heat resulting from electrical transformer losses is an innovative means of heat recovery which is technically and practically feasible and potentially commercially viable as a low-carbon heating solution. A number of both technical factors (transformer size and loading, cooling water temperature, heat pump efficiency) and economic drivers (energy and carbon prices, discount rates) will affect the feasibility of heat recovery systems.

Our modelling framework and analysis show that all heat recovery systems with heat pumps are potentially an attractive option when compared with conventional installations of ground source heat pumps, given that the high cost of installing heat exchangers in the ground can be largely avoided.

5.1 Transformers

Significant efforts are being made to de-carbonise the UK heating sector in line with the national carbon reduction targets[4]. Some heating demand could be potentially met through the recovery of low-grade waste heat from electrical losses in distribution networks. Capturing and using the heat generated by network losses at locations where this heat could be efficiently delivered to customers could improve the overall energy efficiency of electricity distribution. This concept, as shown in Figure 10 may be implemented as a retrofit solution, or may be engineered into the overall network design when new equipment is required. In this context, this section presents the research and analysis conducted to evaluate the potential for using the heat generated by electrical losses in distribution networks[5].

This concept, whilst attractive in principle, requires many challenges to be overcome if technical and practical solutions are to be developed which may be economically feasible:

- Risk to compromising the reliability and safety of the primary plant,
- Matching heat supply to demand,
- Relatively low temperature of the heat source.

[4] Heat Strategy Team, "The Future of Heating: A strategic framework for low carbon heat in the UK", Department of Energy and Climate Change, March 2012. Available at: https://www.gov.uk/government/publications/the-future-of-heating-a-strategic-framework-for-low-carbon-heat.

[5] Although technical solutions for reducing network losses are well understood, at the current rate of network investment it will take decades before the upgrades leading to lower losses improve the loss profile across the network. Therefore it may be concluded that a significant amount of electrical losses will be present for many years. Whatever the level of loss on the network, be it economic or uneconomic, there is opportunity to improve energy efficiency by recovering and using the heat generated by electrical losses in network assets.

In this Report we consider both the potential value of heat from transformers based on analytic modelling work and also considered the past experiences of harvesting and using heat recovered from distribution network losses. We have developed models for assessing the feasibility and potential economic benefits of the use of recovered heat from transformers with heat pump technology using a set of models and life cost methods.

The Study has concentrated on heat recovery from EHV transformers where there is the greatest concentration of usefully-sized electrical loss and therefore the best opportunity for heat harvesting within the distribution network. The Report refers to several installations of heat capture and use. Some of these suggest some good learning experiences which may be usefully applied in future GB developments.

An especially-useful example of heat recovery from transformers has been identified in work by Rook Services working with National Grid. A Case Study is included in the Report describing how heat has been harvested in excess of the heat required for the local offices at the substation. This is a non-intrusive technique which extracts heat from the transformer enclosure and may be compared with more direct (intrusive) forms of extraction where higher-quality heat may be available, but there are more risks to be managed in removing heat if there is no demand.

Recommendation 14: There is opportunity for considerable further learning in Europe and also from National Grid. It would be beneficial to share experiences of waste heat recovery installations among DNOs.

We have considered the viability of heat recovery using a modelling framework that simulates the operation of the main assets involved and the interaction in the heat recovery process.

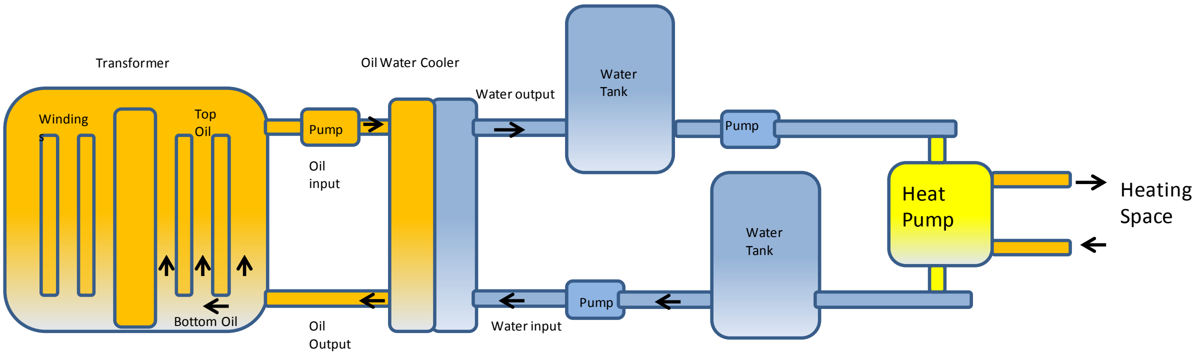

Figure 10. Concept of heat recovery from distribution power transformers

We conclude that the recovery of heat from EHV transformers, which provide the greatest concentration of loss on the distribution network, is potentially commercially viable. Developments to date have demonstrated that this is technically and practically feasible.

Heat recovery systems are likely to be a viable investment when the alternatives are based on electric heaters. Our modelling framework and analysis show that all heat recovery systems with heat pumps are potentially an attractive option when compared with conventional installations of ground source heat pumps, given that the high cost of installing heat exchangers in the ground can be largely avoided. When heat recovery systems are compared with conventional gas boilers, the investment becomes attractive only when the degree of utilisation of heating system is relatively high, although this can be substantially reduced if gas prices and / or carbon cost increase.

Extending the operating time of heating systems by using the heat pump for heating in winter and cooling in summer may be beneficial, although it would add complexity to the system. This topic requires further research, which should also incorporate the capabilities of heat storage to mitigate excesses and surpluses of heat occurring due to diurnal and seasonal variations. Further demonstration projects on heat recovery are recommended in order to further improve the technical knowledge base and better understand commercial performance.

Recommendation 15: An Innovation Project, based upon learning from this initial Study, may be initiated in order to gather further insight into the technical and practical solutions which can be tested at more sites. The Project could be scoped to also tackle the regulatory and commercial market structural issues which will also need to be overcome to bring heat recovery and use into mainstream application.

Recommendation 16: DNOs may maintain an awareness of the potential for heat recovery when planning the installation of EHV transformers and seek to install more systems where the recovered heat may be of commercial use.

5.2 Cables

Heat from cables which are close to and in some cases connected to transformers may contribute to the overall heat available those cases where a non-intrusive recovery system is proposed for the transformer. However there is no evidence of examples of successful heat recovery and use from cables and we conclude that further work in this area is not a priority.

5.3 Opportunities for deployment of heat storage

Our analysis demonstrated that the business case for recovery of low-grade waste heat from electrical losses in distribution networks will depend on the level of coincidence of heat demand and supply. Heat storage could provide additional benefits for heat recovery systems by mitigating the mismatch between heat availability and heat demand over the course of a day or a year. Three types of heat storage are of particular interest for heat recovery applications: 1) ground heat/cool for long-term storage with heat pumps, 2) large-volume insulated water tanks, and 3) smaller Phase Change Modules (PCM). The commercial viability of heat recovery could be enhanced by utilising heat storage, but the benefits of long-term ground storage against short-term water or PCM storage need to be further investigated due to the risks associated with complex systems of this type and increased costs associated with storage related investment and operation costs.

There are an increasing number of ground-based heat storage projects, mainly driven by the need to cool spaces. There are several GI Energy schemes implemented in the UK (Sainsbury's, Carlisle and Crossrail), as well as similar schemes in Finland, Austria and Switzerland. The ground thermal storage concept is readily transferable to heat recovery from transformers and cables, and its implementation should be more straightforward than e.g. the Sainsbury's scheme as it does not require the complicated control system associated with the refrigeration part of the system.

Recommendation 17: Further work on heat storage may be integrated with future trials work on recovery of heat from the distribution network, as it may improve the economics of more basic heat recovery systems.

6 Policy implications of the losses studies

6.1 Ofgem's Business Plan Guidance

The role of Ofgem and their relationship with the networks companies in approving their Business Plans is an important factor in the level of investments made to address losses. Their latest views on DNOs' Business Plans in the RIIO-ED1 price control period 2015-2023 are that more attention should be paid to loss strategy with a new set of obligations and incentives[6].

With ongoing concerns regarding carbon abatement, security of supply and future costs and affordability of energy, Ofgem has provided clear guidance on how loss avoidance may be valued as shown in Table 10.

Table 10. Ofgem guidance on assessment of losses

Factor	Requirement
Cost benefit analysis	Simple discounted approach
Discounting	Applied to all costs and benefits
Treatment of capital costs	Convert to annual cost using pre-tax Weighted Average Cost of Capital (WACC)
Term of assessment	Assumed economic life of the asset up to 45 years
Test discount rate	3.5% for costs and benefits
Value of energy loss reduction	The average of wholesale prices over 2011/12. This is £48.42/MWh in 2012/13 prices.
Value of carbon abatement	DECC's latest valuation https://www.gov.uk/carbon-valuation. For the power sector a linear carbon regression is applied from the present value to 10g/kWh in 2050 in order to reflect decarbonisation policy.

It is clear the choice of a 3.5% test discount rate and 45-year life is very important in providing a bias towards the prudent approach of investing in future networks. By using Ofgem's spreadsheet, a 1MWh reduction in lost energy sustained over 45 years is worth £1,451 in 2012/13 prices.

As demonstrated through our loss-inclusive network design, maximum loading of LV and HV underground network as a percentage of full loading should be no higher than 12-27% of its thermal rating, while for overhead network maximum loading should not exceed 8-19% of the thermal rating. This very significant headroom that is economically efficient will clearly provide a significant hedge against uncertainties of future load and generation growth. Furthermore, the role of alternative smartgrid solutions and technologies in future networks based on loss-inclusive design will shift from enhancing network utilisation to reducing losses.

Recommendation 18: DNOs should develop loss-inclusive network design strategies, based on their specific data, in order to ensure that the overall economic network operation and design criteria are met. This should include network modelling capability for answering "what-if" questions in order to predict the impact of proposed network polices, projects and network demand forecasts on the overall reported network losses.

[6] The previous form of loss incentive within all of the Distribution Price Controls since 1995 has proven to be unworkable due to measurement, recording and reporting difficulties of both technical and non-technical losses.

6.2 Long term electricity and carbon prices

For loss-inclusive design, network policies and network project specifications are significantly affected by the assumption of forward electricity value and carbon abatement values. Already, Ofgem's guidance on future electricity costs support more active consideration of losses in investment decisions. Our analysis demonstrated that the loss-inclusive network design will be sensitive to assumptions of electricity costs.

We note the loss-inclusive network design carried out using the chosen assumptions is perhaps understating the value of loss mitigation as:

a) the average electricity price does not take into account that variable losses are proportional to the square of demand, and are much larger at times of peak network demands, which in general coincide with peak national demand, when the cost of electricity may be significantly higher, and

b) the analysis did not included carbon prices and was based on relatively low energy prices of £45/MWh, particularly in the light of the recent announcement that the strike price for new nuclear would be £92.50/MWh.

Recommendation 19: There is a need to establish the basis for assumptions on future electricity costs and carbon prices that would be used in loss-inclusive network investment that is consistent with the overall UK low carbon policy.

6.3 DNO Business Plans

DNOs Business Plans for the period 2015-2023 have been submitted to Ofgem. In the publication of their assessment of the plans on the 22nd November 2013[7], Ofgem have indicated that in general they wish to see changes to the DNOs' proposed approach to management of losses:

"The majority of DNOs submitted strategies for the management of losses, although we were disappointed across the board with the standard of the associated cost benefit analysis and the level of ambition."

We observe that DNOs have taken different approaches to including losses in their investment decision-making. Within the uncertainties of future needs, it would be desirable to establish a common basis for development of loss mitigation and loss-inclusive network design policies that would be in line with both national interest and DNOs' business objectives.

Recommendation 20: DNOs, with support from DECC and Ofgem, may determine the common basis in relation to loss mitigation and loss-inclusive network design and investment.

6.4 Monitoring and reporting of overall loss levels

It is likely that the overall level of losses for each GB distribution network as a percentage of electricity supplied to the consumer or entering the distribution network will continue to play a part in network loss management. Such a figure is an overall indicator of trends towards an efficient level of losses and it remains an ongoing aspiration of DNOs and Ofgem that the percentage loss may be calculated and/or measured, and to which a reasonable level of confidence may be ascribed. This is not the case at present, and there is insufficient confidence in the reporting of overall loss either as a trend, or between DNOs, or for incentive purposes or for comparing GB with overseas companies. The Report considers the factors which impede the use of the overall loss figures for such management purposes.

[7] https://www.ofgem.gov.uk/sites/default/files/docs/2013/11/assessment_of_the_riio-ed1_business_plans_0.pdf

Ofgem's consultations on the Distribution Price Control loss incentives from 2005-2010 provide an indication of the complexity of loss reporting based upon losses reported through the GB Settlements arrangements. We believe that more detailed analytical work will be required in both the technical and non-technical loss drivers to improve loss reporting.

Whilst the loss incentive has been abandoned for the RIIO-ED1 price control period, it is important that an early start is made to planning how losses are going to be measured and reported more accurately in the future. Ofgem's aspiration is to return to a loss-incentive mechanism in RIIO-ED2 from 2023 onwards. Whilst it may seem that this is sufficiently far into the future to not be today's priority, it is likely that significant lead time is required to develop new measuring and reporting systems, and an early start is required. This is especially the case in order to have confidence in a new measuring regime before negotiations on RIIO-ED2 commence.

Whilst meeting Ofgem's requirements is an important motivator towards better loss measurement and reporting, networks strategists and managers will also have increasing confidence in their decision-making if their policy and planning activities are informed by better data on losses. Although many key network decisions may be location-specific and there is limited use which can be made of the overall loss reports in practical network design work on specific parts of the network, they remain an important performance indicator.

Recommendation 21: Early in the RIIO-ED1 period, DNOs may develop more accurate means of measuring and reporting of distribution network losses.

The disparity in reported losses between Government (DUKES data) and Ofgem has been identified in the Report, see Figure 11. The Ofgem figures have been the focus of attention, and in our view provide a more appropriate reflection of reality as work has been done on the "raw" data to factor-in adjustments, in particular those relating to Settlements reconciliations.

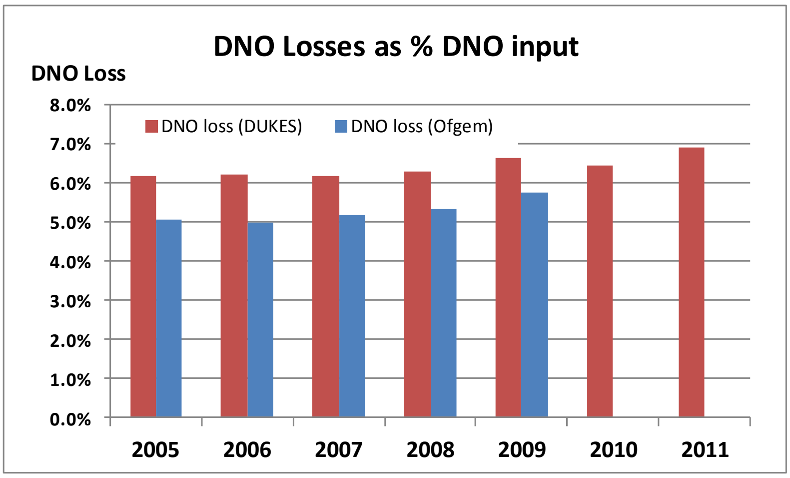

Figure 11. Reported losses from DUKES and Ofgem

The DECC reports may be of less significance and of less relevance to the interests of DNOs. However, there is a risk that the DECC data is used by Government and is also collected and used internationally, possibly presenting GB losses as high when making international comparisons. We do not believe that this is in the best interests of GB DNOs and it is a matter which DNOs should address.

Recommendation 22: The DECC/Ofgem comparison of reported losses shows a discrepancy which may cause a distorted view of GB DNO losses, within industry, government and internationally.

6.5 International comparisons

The Report includes comparisons of network losses in various countries and describes the factors affecting the validity of the comparisons. GB DNOs may be disadvantaged by misleading comparisons due to the inconsistent approaches to reporting between countries and, whilst this is not a priority requiring change, DNOs may seek to qualify the comparisons being made when suitable opportunities arise to influence opinion on the international stage.

Recommendation 23: DNOs may grasp opportunities as they may arise to influence loss reporting in other countries and as it is presented in international studies. This is in order to ensure that GB DNOs' loss management performance is presented accurately.

6.6 Policy to facilitate waste heat recovery

A number of supporting mechanisms can be expected to apply to heat recovery in the near future. Heat recovered from transformers and utilised instead of fossil fuel sources will benefit from avoiding carbon taxes such as the Climate Change Levy (CCL), the European Union's Emissions Trading System and the new carbon price floor mechanism. Avoidance of the latter is likely to prove particularly attractive if it is implemented as planned. In addition, it is possible that waste heat recovery from transformers could benefit from enhanced capital allowances in future if the technology was deemed eligible.

Heat pumps systems that combine heat recovery from transformers might also benefit from the Renewable Heat Incentive (RHI) in future. The use of a non-natural heat source, such as heat from a transformer, disqualifies a heat pump system from the RHI subsidy under current legislation. However, DECC are currently considering arguments for the proportion of naturally occurring heat extracted from the ground or the air, which is defined as renewable, to be eligible in future provided that the overall system meets the required technical standards.

Recommendation 24: Industry, government and regulators should consider developing appropriate regulatory and commercial frameworks that would facilitate development of loss-generated heat schemes where economically justified.

6.7 Barriers to implementation

The concept of providing an energy-efficient distribution network is clear and in principle is highly desirable. The question therefore is why has this not been achieved? Barriers to loss-inclusive design are largely historic, including lower valuations placed on avoided loss, lack of understanding of the size and location of losses, lack of information, unworkable incentives and targets. It is also likely that network management culture has played a part, as losses have not been considered as a primary driver in network design, and certainly not comparable with network safety and reliability.

One of the key questions to be answered is the requirement for loss standards, whether incorporated as best practice guidelines to be generally followed based upon the forward valuation of energy and today's equipment costs, or obligated more prescriptively through a Distribution Licence obligation. There will be many views on how these barriers may overcome and how loss-inclusive network design may be delivered. We believe that the work reported here is the start of a journey taking GB networks businesses forwards to operate on the principle of loss-inclusive network design. Strategic decisions are required with which to move the loss agenda forwards to this extent. It is our view that a critical success criterion for future loss strategies is that the network operates at an economically efficient level based upon the best assumptions that can be made of future network requirements. It is also our view that further work is required on loss strategies in order to achieve this.

Recommendation 25: DNOs' loss strategy may be "stress tested" to demonstrate that it can deliver an objective of achieving an economic level of losses based upon avoided loss valuation, engineering costs and future network demands.

7 Conclusions and Next Steps

Supported by the illustrative analysis of losses and cost-benefit studies plus research, we conclude that:

- Network losses should be included within network design policy and that network energy efficiency should rank alongside safety and security of supply in the objectives of overall network management;
- There are several economically viable interventions on existing networks which, together with new design policies, which will enable the move to higher network energy efficiency;
- There is evidence of technical and practical solutions to harvest and use heat generated by electrical loss in order to improve overall energy efficiency of running the network. However, more work is required if the developments are to be deployed in those cases where there may be a match between heat demand and heat generation from the network.

We trust that this Study has illustrated the potential for loss management and that DNOs may adopt the proposals and take actions to embrace the principle of loss inclusion in network management. The Recommendations in our work are listed in Annex 1 to this Executive Summary.

To move forwards, we would anticipate that DNOs may develop a long-term plan to discover new knowledge of network losses and to develop network policies, standards and network designs for future networks which may be demonstrably best practice in electrical power distribution.

Annex 1: List of Recommendations

(Including page numbers)